The dust and gas content of a disk around the young star HR 4796A

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Abstract

We have used the *James Clerk Maxwell Telescope* (JCMT) in Hawaii to search at submillimetre wavelengths for continuum emission from dust, and spectral line emission from carbon monoxide (CO) gas, in the neighborhood of HR 4796A. This young star has a dusty disk with a central cavity, where planets may have formed. We detect the dust component at a wavelength of 850 μm, and the inferred mass of solid material is ≥ 0.25 $M_\oplus$. An upper limit for the CO J=3–2 rotational line implies less than 1–7 $M_\oplus$ ($\leq$ 0.003–0.02 Jupiter masses) of molecular H_2 gas in the system. Thus, it is no longer possible to form new Jupiter-like gaseous giant planets around HR 4796A. If planet formation explains the observed dust cavity and lack of gas, then it must have occurred before the current stellar age of $\sim$ 10 million years (Myr).

A search was also made for CO J=3–2 emission around four other stars with dust excesses revealed by infrared measurements with the *Infrared Astronomical Satellite* (IRAS). Two were detected, both of them young sources with optical emission lines indicative of ongoing accretion of disk material onto the star. The gas mass lower limits are approximately 30 and 200 Earth masses, at least an order of magnitude higher than for HR 4796A, illustrating the diversity of disk properties at ages of up to 10 Myr.

Introduction

HR 4796 is a binary star at a distance $d = 67$ pc. The primary, HR 4796A, has a spectral type of A0. The secondary is an M2.5 star, and the projected separation of the two components is currently 515 AU (Jura et al. 1995.) We consider here excess emission (above the photospheric level) from material orbiting around the primary. With an age $t = 8 \pm 2$ Myr (Stauffer et al. 1995), the environment of HR 4796A is roughly mid-way in an evolutionary sense between the massive pre-planetary disks of gas and dust orbiting young ($t \sim 1$ Myr) pre-main-sequence stars (Beckwith & Sargent 1993; Mannings & Sargent 1997) and the low-mass secondary debris disks surrounding main-sequence stars ($t \sim 100$ Myr) such as β Pic, α PsA, α Lyr and ϵ Eri (Backman & Paresce 1993; Greaves et al. 1998; Holland et al. 1998a; Mannings & Barlow 1998). The latter disks are thought to be composed of debris products generated in collisions and disruptions of asteroid-sized bodies formed earlier on during the massive disk phase. HR 4796A appears to be at the stage where a formerly massive primary disk has evolved into planetesimals and (perhaps) planets, with a secondary disk of debris grains. It is this secondary disk we detect in submillimetre emission.

Observations

The new data were obtained at the JCMT between February 1995 and May 1998. The 850 μm continuum emission towards HR 4796A was detected with the new *Submillimetre Common-User Bolometer Array* (SCUBA) (Holland et al. 1998b), and the CO J=3–2 spectra (345.796 GHz) were observed with the B3i receiver. Integration times were 1 to 4 hours for the spectral lines and 30 minutes for the dust photometry. The data were taken by chopping the secondary mirror to remove sky emission, and calibrated using standard sources and sky opacity measurements. The CO data have been converted to a main-beam antenna temperature scale.

Thermal emission from grains in the vicinity of HR 4796A was detected at 850 μm, with a flux density of 19.1 ± 3.4 mJy. This corresponds to 0.25 $M_{\oplus}$ of dust, for a grain temperature of 90 K (cf. models of Jayawardhana et al. 1998; Koerner et al. 1998) and an opacity of 1.7 cm^2 g^{-1} (cf. Holland et al. 1998a). This value is likely to be a lower limit to the mass of material encircling HR 4796A as very large grains and planetesimals might dominate the mass while emitting little submillimetre emission. We cannot yet determine grain sizes using the submillimetre spectral index, but better constraints may be possible with a deeper integration: SCUBA data obtained simultaneously at 450 μm wavelength currently indicate a flux density $\sim$ 180 $\pm$ 150 mJy. Our mass estimate is comparable to the reported $\sim 1\ M_{\oplus}$ from fits to the mid-IR to submillimetre spectrum (Koerner et al. 1998; Jura et al. 1998).

We did not detect any CO emission towards HR 4796A, after a 4 hour integration. The 14″ telescope beam (full-width at half-maximum) was centred on the A0 star HR 4796A and its 3″ diameter dust disk, and included the companion star HR 4796B at approximately the 40% power-point of the beam, for its projected offset of 7.7″. Thus there is no evidence for molecular gas around either star.

Our CO J=3–2 spectrum of the HR 4796 system is shown in Figure 1. There is no emission at the heliocentric velocity of +6 km s^{-1}, with an upper limit of 9.0 mK rms for an 8 km s^{-1} spectral channel. This is the velocity range for significant emission in a model described below, of an edge-on disk with an inner cavity (Jayawardhana et al. 1998; Koerner et al. 1998) around a 2 $M_{\odot}$ star.

— *Figure 1* —

For comparison, we also searched for CO J=3–2 emission around four stars with significant IRAS excesses attributed to dusty disks (Sylvester et al. 1996). HD 34282 and HD 169142 were detected in CO (Figure 1) with integrated intensities of 1.24 and 2.35 K km s^{-1} respectively, while limits for HD 49662 and HD 144432 were $\sim$ 0.2 K km s^{-1} over a 5 km s^{-1} interval. These stars are all likely to be pre-main-sequence objects with ages of a few Myr (although Oudmaijer et al. (1992) suggest a post-main-sequence component in HD144432). The two detected objects both have IR–mm spectral energy distributions (SEDs) reminiscent of those of Lada Class II T Tauri stars surrounded by massive disks (cf. Sylvester et al. 1996).

Both of the sources we detected in CO J=3–2 are young stars, as they have optical emission lines. This trend towards CO detections in younger objects agrees with the results of Zuckerman, Forveille & Kastner (1995); combining the dwarf (V-type) stars in both datasets, CO is detected towards 5 of 7 emission-line sources but only 3 of 8 of the nonemission line objects. This result supports a short timescale for molecular gas to remain in these systems, before it is incorporated into planets, dispelled by stellar winds or accreted onto the central stars. The statistics can not be explained by a selection bias, as the median distance is in fact larger for the emission-line stars, so the signals would be weaker for comparable gas masses and temperatures.

Model results

A simple model has been used to estimate the gas masses in these systems, based on the approach of Yamashita et al. (1993). We assume wedge-shaped disks with H_2 number density proportional to radius to the power −2.5, circular Keplerian orbits, and gas excitation in thermal equilibrium with blackbody grain temperatures (Eq. 3 in Backman & Paresce 1993). In the model, molecules are distributed between cells, and local thermodynamic equilibrium calculations (including optical depth for the velocities within each cell) give the contributions to the spectrum. The $CO:H_2$ abundance is affected by photodissociation from interstellar UV radiation (van Dishoeck & Black 1988) and also by the stellar UV field at the inner edge of the disk. The models of Hollenbach et al. (1991) were used for the relation of $CO:H_2$ to the extinction A_V towards the star (neglecting any density dependence) and standard UV fields were used the stellar types (A0 for HR 4796A and HD 34282; B9 for HD 169142). We neglected photodissociation of H_2 which is significant only over a narrow A_V-range (van Dishoeck & Black 1988), and CO freezing onto grain mantles, which is important only at very large radii where temperatures fall below about 30 K (Sandford & Allamandola 1993).

Figure 1 shows example fits to the spectra, matching both the integrated intensity and the line shape (with a reduced-χ^2 criterion of $\geq 10\%$ fit probabilities). The distance estimates are the major cause of uncertainty for HD 34282 (160^{+60}_{-40} pc, van den Ancker et al. 1998) and HD 169142 ($\sim$ 145 pc, Sylvester et al. 1997), as the fits are constrained largely by the beam-filling factors of these optically-thick, self-shielded disks. We find minimum disk diameters of a few hundred AU, CO line opacities > 7 and minimum gas masses of ~ 0.1 and 0.7 Jupiter masses respectively. Massive disks are expected as Sylvester et al. (1996) detected high 1.1 mm dust fluxes; this would also be consistent with the Lada Class II stellar identifications.

In contrast, the gas mass for HR 4796A is at least an order of magnitude lower. The adopted disk parameters were outer radius 125 AU, inner radius 30–50 AU, inclination of $\geq 72°$ (where $i=0°$ is face-on), and an opening angle of 5–20°, imposed by the thin and nearly edge-on appearance in 20-μm images (Jayawardhana et al. 1998; Koerner et al. 1998). The CO upper limit then implies a low $M(H_2)$ of $\leq$ 1.1–7.3 $M_\oplus$, with the range depending largely on the adopted disk thickness, which affects the photodissociation. Unlike the other two disks, the $CO:H_2$ abundance is significantly reduced, to $< 3 \times 10^{-5}$ compared to interstellar values $\sim 2 \times 10^{-4}$, and the gas is optically thin with τ(CO J=3–2) less than 0.3. For a dust mass of ≥ 0.25 $M_\oplus$, the gas-to-dust ratio must be $\leq$ 4–29, i.e. depleted by a factor of at least ~ 3 with respect to molecular clouds (gas-to-dust ≈ 100; e.g. Hildebrand 1983). We cannot constrain the mass of any atomic HI gas, but this should be diffuse and unlikely to be associated with condensed planet-forming regions.

Discussion

The dusty disk around HR 4796A has been detected in submillimetre emission, and the mass is consistent with estimates from 20 μm data (Koerner et al. 1998), implying that the grain properties are moderately well understood. Modelling of the CO abundance and line upper limit implies an H_2 gas mass below 7 $M_\oplus$ and consequently gas-to-dust depletion of at least a factor of ~ 3 relative to molecular cloud material. The remaining molecular gas in the HR 4796 system is much less than is needed to make a Jupiter-like planet — at most, a gas 'subgiant' with half of Neptune's mass could be constructed. Thus, any Jovian planet formation should be complete around HR 4796A, even at the young age of 8 ± 2 Myr (Stauffer et al. 1995). In contrast, CO was detected around two young stars, both with emission lines, and the minimum gas masses are at least an order of magnitude higher than for HR 4796A. Thus there is considerable diversity in the disks around intermediate-mass stars, at ages of up to 10 Myr.

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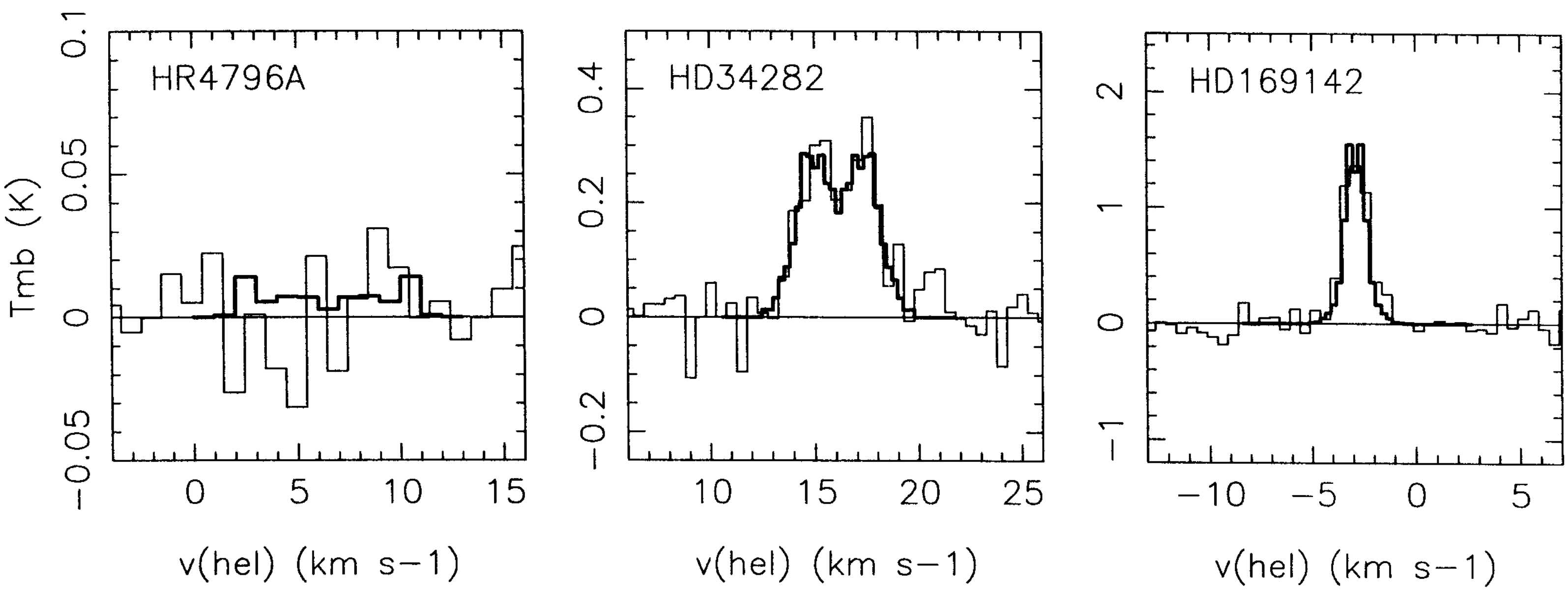
Figure 1. CO J=3–2 spectra for HR 4796A, HD 34282 and HD 169142, overlaid with model spectra (thin and thick histograms, respectively). For HR 4796A the model is for the maximum allowed gas mass, constrained by the CO upper limit and the orbital velocities in a 50–125 AU radius disk. The models for the other two stars are for the minimum gas masses, as described in the text.


HR4796A
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